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A Decision Support Tool (R-SWAT-DS) for Integrated Watershed Management

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A Decision Support Tool (R-SWAT-DS) for Integrated Watershed Management

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Abstract: Best management practices (BMPs) can be used effectively to reduce nutrient and sediment loads generated from point sources or non-point sources to receiving water bodies. Methodologies for optimal, cost effective BMP selection and placement are needed to assist watershed management planners and stakeholders. We developed a modeling-optimization framework that can be used to find cost-effective solutions of BMP placement to attain nutrient load reduction targets. The framework integrates the Soil and Water Assessment Tool (SWAT) watershed model, spatial representation of BMPs, an economic component, and multi-objective optimization routines in the R environment. The framework can be used to launch individual or iterative BMPs simulations, or search for optimal strategies. Advanced plotting, mapping and statistical analysis functionalities that facilitate the interpretation and assessment of the results are included.

Keywords*:* Multiobjective; Best management practices (BMPs); SWAT, Nutrient Loss, Sediment yield

1 INTRODUCTION AND SCOPE

Water availability is often jeopardized by poor quality and contamination problems that severely reduce the number of potential uses of this precious resource. Water systems are subject to increasing threats such as over-exploitation, and rising levels of contamination from point (PS) and diffuse sources (NPS) of pollution. Water flows are essential for agricultural systems, and for all the ecosystem services that rely on their quantity and quality. Natural resources exploitation in the absence of conservation practices may trigger environmental degradation processes in a watershed, such as increased runoff and sediment and nutrient losses, which can compromise the quality of the water resources and increase the vulnerability of the local freshwater ecosystems (Yang et al. 2009; Bouraoui and Grizzetti 2011). In this context, it has become vitally important to develop and apply new management strategies and methodologies able to reverse negative trends in water quantity overuse and quality degradation.

Best Management Practices (BMPs), including conservation, restoration and modified management practices, may effectively reduce the threats and enhance local and regional water quality and availability. Watershed simulation models are powerful tools to inform and support watershed decision-making and planning, for example by enabling assessment of different management scenarios (Lenhart et al. 2002). The Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) is a comprehensive process-based integrated basin model that considers several ecohydrological functions, providing for assessments of water quantity and quality in small to large watersheds. The model involves a large number of components, and it is widely used to predict the impact of management practices in aquatic environments (surface and underground) in complex watersheds, accounting for soil type, land use, application of fertilizers and pesticides, and the conditions of watershed management (Arnold et al. 1998). Several studies used SWAT to address BMP optimization (Arabi et al., 2006; Babbar-Sebenset al., 2013; Ghebremichael et al., 2013; Gitau et al., 2004; Hoqueet al., 2014; Maringanti et al., 2009).

However, methodologies for cost-effective BMPs selection and placement in a watershed are needed to assist watershed management planners and other stakeholders to address water issues at various spatial and temporal scales and to facilitate actual implementation (Yang and Best 2015). Targeting implementation of BMPs to critical locations in a watershed has been recognized as an effective strategy to improve water quality (Zhen et al. 2004). The identification of efficient conservation strategies (BMPs) is a challenging spatial optimization problem that must consider location specific characteristics and economic indicators.

The aim of the work was to develop and apply a simulation/optimization framework to identify cost-effective management strategies to reduce nutrient pollution. The Decision Support Tool (R-SWAT-DS) is developed in R-programming, able to assess the contribution and effectiveness of different management strategies in reducing environmental impacts at low economic cost. We hypothesize that reductions of pollutants in the river network can be achieved at significantly lower cost by optimizing the combination of spatially targeted PS and NPS conservation measures. In our study we used the biophysical SWAT model (Neitsch et al. 2011) to simulate point and diffuse nutrient emissions and fate in a watershed. The framework was developed in the open-source programming language R (R Development Core Team, 2011) and can be used to launch individual or iterative BMPs simulations or search for optimal strategies. It includes advanced plotting, mapping and statistical analysis functionalities to facilitate the interpretation and assessment of the results, and can accommodate alternative simulation/optimization methods.

2 THE R-SWAT DECISION SUPPORT FRAMEWORK (Software design and characteristics)

The R-SWAT-DS is a framework developed to help stakeholders in the selection of BMPs related to nutrients pollution reduction. It includes the following main components: (1) a watershed biophysical model (the Soil and Water Assessment Tool, SWAT; Arnold et al. 1998) for simulation of hydrologic and water quality processes under pollution control (restoration) scenarios; (2) a component to link the biophysical model to R; (3) an economic module to estimate the monetary value of each management scenario; (4) an optimization engine to search for trade-off restoration scenarios according to environmental and socioeconomic objectives. The framework can model nutrient reduction measures related with PS (WWTP upgrading) and NPS (crop fertilization and irrigation strategies).

2.1 Programming Environment features

The decision support and management framework is required to handle a high quantity of data, to visualize graphics and reports, and to be flexible and sharable. Flexibility means the possibility to adapt easily to new needs and requirements coming from end users. An open-source software ensures the capability to share code and routines. Furthermore, open source software guarantees transparency, which allows full scrutiny of the techniques applied.

In this context R was chosen has an appropriate platform and language for the development of the tool. R (www.r-project.org) is an open-source programming environment that is rapidly taken up across a wide range of disciplines (R Development Core Team, 2011). It is an interpreted language that offers excellent interactive analysis capabilities and is ideal for development of statistical data analysis applications. It is very robust and works on a wide range of platforms including Microsoft Windows, Apple OS X, and Linux. The already large collection of user-contributed R packages containing state-of-the–art functions/algorithms used in many different fields (see e.g. http://cran.r-project.org/web/views/) continues to grow exponentially (Fox 2009). These packages are freely available for public scrutiny, thus resulting in a continuously peer-based quality-control system.

For water resources management purposes, R represents the ideal system to work with. Core features such as effective data manipulation, data/statistical analysis, high quality graphics and visualisation lend themselves to analysing water pollution data. The R-SWAT-DS framework takes advantage of specific R Packages created to modify the SWAT input files or read output files (Zambrano and Rojas, 2013) and to implement mono and multi objective optimization techniques (Cortez, 2014).

2.2 The SWAT model

The Soil and Water Assessment Tool (SWAT; Arnold et al. 1998; Neitsch et al. 2011) was used to assess the impact of point sources and land use management practices on hydrologic and water quality processes, as well as on agricultural yields. The SWAT model integrates all relevant eco-hydrological processes including water flow, surface runoff, percolation, lateral flow, groundwater flow, evapotranspiration, transmission losses, nutrient transport and turn-over, vegetation growth, land use, and water management. The simulation of watershed hydrology with SWAT is divided into two main phases: the land phase and the routing phase of the hydrologic cycle, which controls the amount of water, sediment, and nutrients into the main stream network. Essentially, SWAT uses the water balance approach to simulate watershed hydrologic partitioning (Neitsch et al. 2011). Watersheds are divided into spatially linked subbasins; the subbasins are subdivided into unique Hydrological Response Units (HRUs) with unique soil/land use and slope characteristics. The land phase is solved at HRU level, which determines water flow and nutrient load outputs to the stream; in the water phase, these outputs are routed through the subbasin and the stream network till the watershed outlet. Agricultural management practices, such as planting, harvesting, tillage, irrigation, grazing and nutrient applications can be simulated with specific dates. Irrigation and fertilization can be additionally applied automatically according to crop water and nutrient stress. The crop growth component of SWAT is a simplified version of the Environmental Policy Integrated Climate (EPIC) model (Williams, 1995), and simulates a wide range of crop rotation, grassland/pasture systems, and trees.

2.3 R-SWAT Decision Support Description

The R-SWAT-DS framework was designed as an integrated catchment management decision support tool, and is implemented as a set of coded scripts using R programming. It assesses the economic and water quality impacts of different types/levels of management practices, and compares them with the Baseline Scenario (BS). It can apply different BMPs at different location, thus allowing to evaluate their overall impact and search for spatial combinations that are most effective to improve the water quality at a minimum cost. The tool enables spatially explicit decision-making and moves away from "blanket" policies, helping stakeholders to better understand the main water quality problems and finding the most efficient practices for a given watershed.

The framework communicates with the SWAT model through simple ASCII files and/or R wrapper functions (Fig. 1), that modify model input files and read outputs files. Users of the R-SWAT-DM tool need to provide the path where the SWAT model is located and create a folder with files corresponding to the Baseline Scenario. They must also create a folder to store information related to the economic model such as crop prices, fertilizer costs, fixed costs, and Waste Water Treatment Plants (WWTP) cost coefficients. Users can run single or combined simulations of spatially explicit management practices, or iterative simulations whereby all management practices of one type are changed simultaneously step-wise in a fixed range of values. Alternatively, they can also choose to run a multi-objective optimization process. In this case, users should specify the environmental objective, choosing among the available options, the management practices to be considered, e.g. WWTP, fertilization and/or irrigation, and the optimization process parameters. Once the simulation and/or optimization process has finished, the user can analyse and compare the management scenario outputs graphically and statistically. The framework can also generate maps with detailed spatial information about a selected scenario.

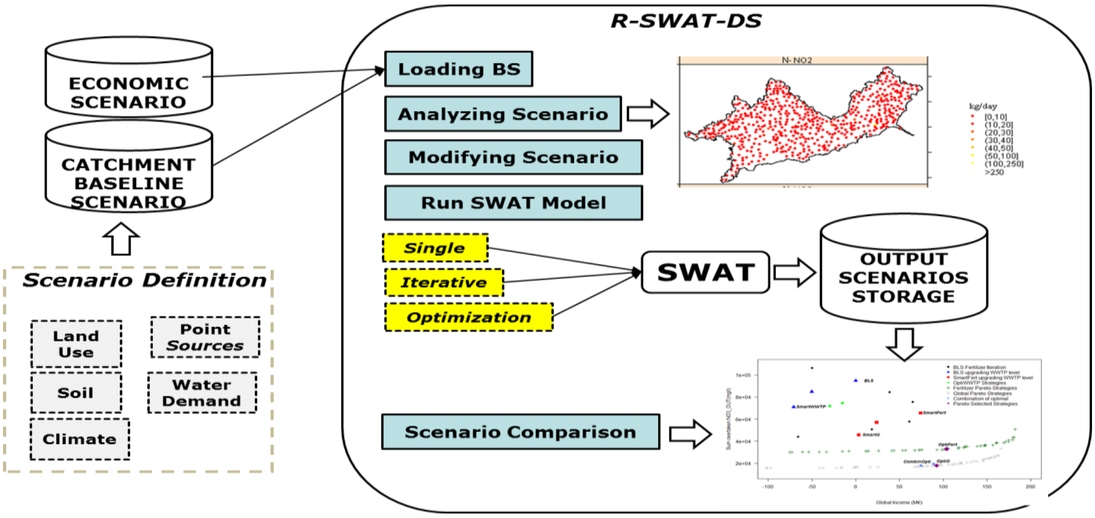

Figure 1. Flowchart describing the interactions of the main R-SWAT-DS functions.

3 EXAMPLE OF R-SWAT DECISION SUPPORT USAGE AND CAPABILITY

This section demonstrates the usage of a few R-SWAT-DS functions. While it is not possible to cover many functions in depth, the examples below highlight some of the underlying principles of usage. R itself works well in an interactive way e.g. the results from an analysis suggest a refinement or point to the use of another function. Because the feedback to the user is almost immediate, a large analysis can be conducted quickly.

3.1 Loading Baseline Scenario Information (model setup calibration)

The basic information for the R-SWAT-DS comes from the SWAT baseline scenario of the watershed. In order to use R-SWAT-DS with confidence, the hydrological model has firstly to be calibrated for the Baseline Scenario (BS). Once the hydrological model is calibrated information from BS can be extracted and analysed. In this example the main information are related with contamination point sources (PS) and diffuse sources (NPS). For each PS in the watershed, a text file must be created that contains all relevant information: e.g. emissions of flow, nutrient concentrations, sediments, etc. The function `LoadingPS()` reads and stores all these data. Similarly, the function `LoadingNPS()` creates text files that stores all NPS information, i.e. HRU management: crop, area, irrigation, fertilization, etc.
BMPs implementation and maintenance come at a cost. These costs have to be spatially quantified and optimized. The system uses SWAT outputs on crop yield and combines it with crop price, fertilizer cost, irrigation water availability, irrigation water cost, standard operational cost, and crop fixed cost (including seeds cost, tillage operations, machinery, grain drying, labor, etc.). It also extracts water quality outputs across the river network. Waste water treatment plant (WWTP) efficiency and costs are also included. More specifically, different WWTP technologies providing for different efficiencies of pollution removal can be introduced in the system to be analysed as a management option with its associated costs, which include initial investment and operational costs. Economic information is managed through the function `LoadingEconomy()`.

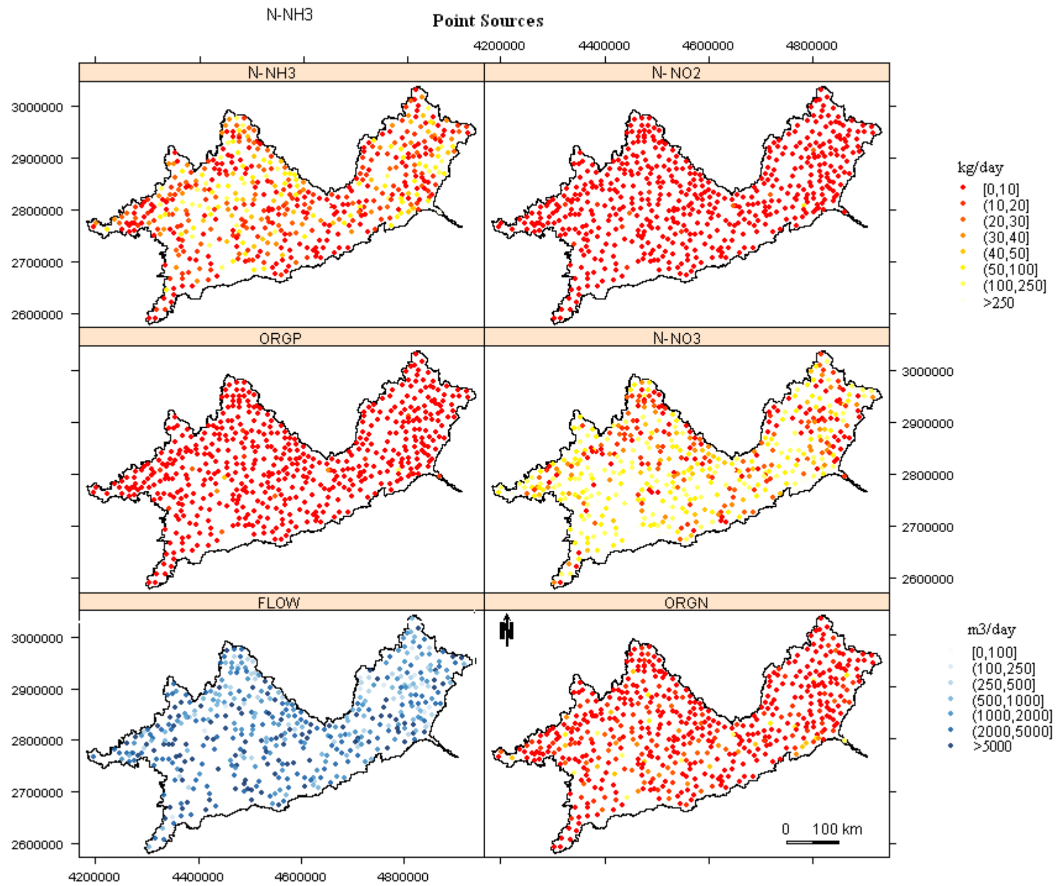

Figure 2. Map of point sources flow (m3/day) and nutrients concentration (kg/day).

3.2 Scenario Information Summary and Visualization

Most users build their watershed SWAT scenarios from a wide variety of information (land use, climate data, hydrological data, etc.). Before starting the management scenario analysis, it is very useful to examine and properly display some of the characteristics of the watershed. The framework includes some functions that perform diverse scenario information summary. Good examples are the function PointSourcesSummary(), DiffuseSourcesSummary(), PointSourcesPlot() and DiffuseSourcesPlot(). The PointSourcesSummary() function create summary report about the PS flow, nutrients concentration and sediments. The PointSourcesPlot() create maps with the same information (see figure 2). In a similar way DiffuseSourcesSummary () function create summary report by HRU and time period of land use, fertilization, irrigation, crop yield, etc. The DiffuseSourcesPlot()create maps with this information.

3.3 Modifying Management Practices

One of the most interesting features of the framework is the possibility to perform what-if scenario analysis for different BMPs. Two groups of watershed management practices have been considered: one related with NPS and one with PS. So far, two functions have been implemented: ModifyFert() and ModifyIrr().

ModifyFert() automatically applies modification to the BS related to the fertilization management. It is possible to adjust the amount of fertilizer applied in each single HRU (relative to that applied in the BS). Alternatively, it is also possible to apply the same percentage of variation to all the HRUs with the same crop in the watershed. In both cases the amount of mineral and organic fertilizers can be varied independently. Similarly the ModifyIrr() function performs a rate of variation (related to the BS) in the irrigation applied in each HRU or in all HRUs with the same crop. The user can also choose to use the SWAT auto irrigation option.

Improved sewage treatment can substantially reduce PS pollution. The PS management practices allow the user to create modified scenarios in which the type of existing WWTP is upgraded. The user can upgrade WWTP to any level of purification for which information is provided, globally, i.e. by applying the same new level to all PS, or individually to each of them.

3.4 SWAT scenarios Model Running

The function RunSWAT() executes a given SWAT management scenario. Moreover, the function ExecutionRun() allows different types of execution and controls the creation of the modified scenario, by calling ModifyScenario (), which execute the scenario, and ReadScenarioResult(), which reads the scenario results(). R-SWAT-DS can be used to perform three types of executions: single, iterative and optimization. If the case of a single execution, the tool creates a new scenario modifying the BS management according to user preferences. In this case the new rate of fertilization and irrigation in each HRU and upgrading in each WWTP to be changed (simultaneously or not) must be specified and stored in a ASCII file. In the case of iterative execution, the new rates for modifying all HRUs with the same crop or all WWTPs can be introduced either by a file or directly in the tool. In this case the tool performs a series of individual executions. An example could be to analyse the effect of the amount of fertilizer applied in a basin. The user must specify the minimum, maximum and the step increase rate of fertilizer (related to baseline scenario), and the tool iteratively generates runs and reads the results of each of the scenarios. Finally, the tool includes the optimization execution type, in which it searches for best management practices allocation that fulfils the criteria selected by the user.

3.5 Multi-Objective Optimization Execution

Multi-objective optimization approaches can determine a set of non-dominated solutions belonging to a Pareto-optimal front. Since the shape of the objective function cannot be assumed as smooth or differentiable in any watershed management problem, gradient free methods such as evolutionary algorithms are applicable as optimization method. To solve this optimization problem, the R-SWAT-DS integrates the nsga2Rpackage (Tsou 2013) to implement the non-dominated sorting genetic algorithm NSGA-II (Deb 2001), which is among the most commonly used multi-objective global optimization methods, counting numerous successful applications in watershed management (Bekele & Nicklow 2005; Muleta,& Nicklow 2001; Udías et al. 2012).

The optimization option is a logical approach for targeting PS and NPS pollution control practices. Under this problem, the objective functions are often conflicting and incommensurable and drive to a multi-objective problem following the next equation:

$$\begin{cases} minimize \;\; Pollutant\ concentration\ load(s) \\ \qquad maximize \;\; Global\ benefit(s) \end{cases} \qquad (1)$$

To run a multi-objective optimization process in the R-SWAT-DS framework, the user should select at least two objectives. Usually at least one should refer to the environmental objective, e.g. selecting a constituent of interest such as NO_3, NH_4 or PO_3. For the economic objective, the user could choose to maximize the total net income, or to minimize the investment in WWTP, or to maximize the gross margin for the farmers. Placement of BMP combinations was planned at the HRU level for fertilization or irrigation options.

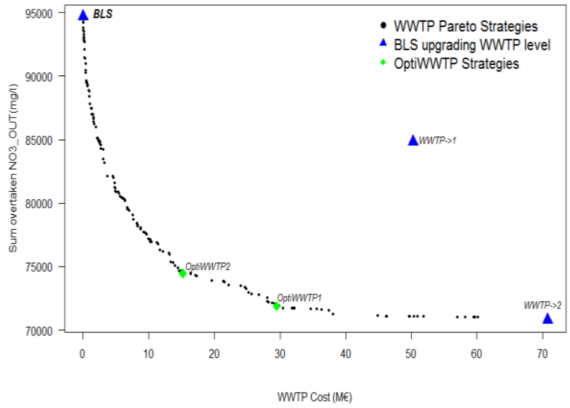

Figure 3. Example of Pareto front WWTP upgrading strategies according to two criteria.

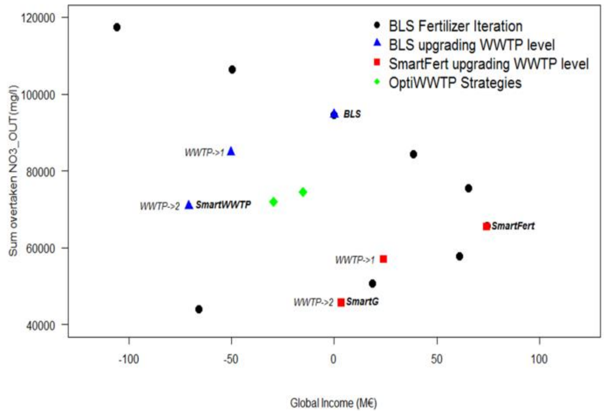

Figure 4. Example of iterative and single scenario strategies according to two criteria.

3.6 Results Analysis and Visualization

A key element in any decision-making process is the analysis and visualization of results. R-SWAT-DS includes a large number of functions that greatly simplify the task. ComparingScenariosSummary() provides straightforward, commonly used numeric model evaluation statistics. It creates reports that compare scenarios generated from different management alternatives. It can simultaneously compare scenarios generated in the single or iterative mode as well as the Pareto efficient solutions from the optimization process. Among other things, the function generates summary tables with multiple statistical values for different pollutants, the total agricultural production, income, gross margin, profit, irrigation, amount of fertilizer, etc. ComparingScenariosPlot() creates a two dimension plot showing all scenarios results according to two objectives. NutrientsScenMaps() creates spatial maps showing the nutrient status according to a specific scenario. AgriScenMaps() creates for one specific scenario, actual and BS comparative spatial distribution maps showing the yield, irrigation, fertilization, nutrients percolation, etc. PSScenMaps() creates maps of the upgrading type for each WWTP in the region.

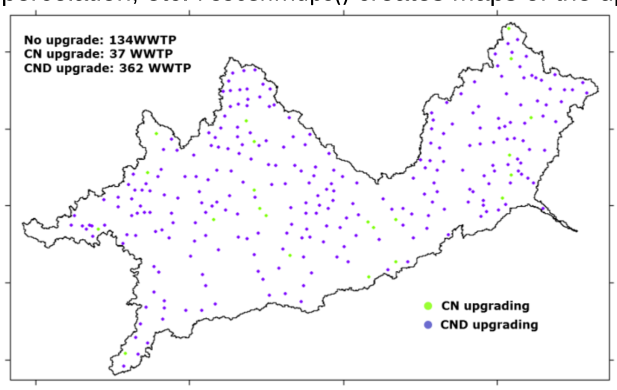

Figure 5. WWTP upgrading distribution map according to the optimal management strategy.

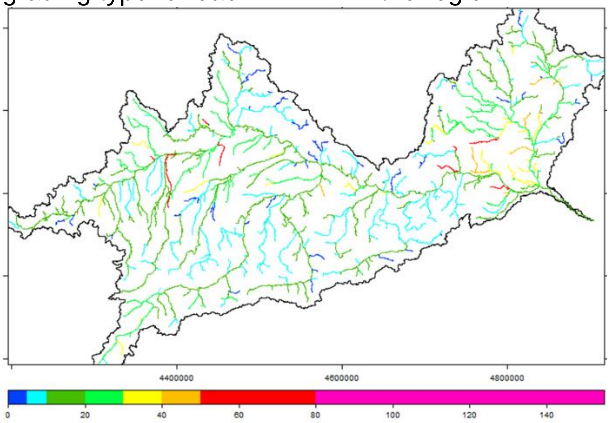

Figure 6. Monthly N-NO3 concentration average (mg/l) in the Upper Danube reaches under Optimal management strategy.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

An integral simulation-optimization framework (R-SWAT-DS) for optimal allocation of PS and NPS conservation practices was presented in this paper. The framework uses the spatially distributed watershed model Soil and Water Assessment Tool (SWAT) to assess nonpoint and point source pollution and crop yields under current conditions (baseline) as well as under alternative management scenarios. Management strategies included crop fertilization plans to reduce diffuse pollution and wastewater treatment plant technology upgrading to reduce PS pollution. The economic module allows evaluating the economic benefit or cost associated to each management strategy, accounting for farmer's net income and WWTP upgrading investment cost.

One of the most interesting features of the R-SWAT-DS framework is that with very little computing time it gives decision makers a good picture of the environmental situation of the study region, allowing exploring the maximum improvements that can be achieved with each individual management practice or with their combination. It also provides an evaluation of the costs (or potential income) required to afford any conservation strategy. The visualization tools included in the framework help to identify areas that are most polluted (or at risk of pollution) and the spatial distribution of the improvements that can be afforded with a conservation strategy. The tool provides Pareto optimal strategies, especially useful in the definition of the improvements that can be expected and for the identification of trade-offs between environmental and economic objectives.

During the development phase of the scripts that make up the current version of the software, the R-SWAT-DS tool was applied in different basins with very satisfactory results from the point of view of decision support. Since the tool can be very useful in a number of watersheds, we have begun to work on the preparation of an R package that will include all scripts and functionalities described in this paper.

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